Provenance of the c. 390 Ma HP–HT subducted continental margin (Variscan belt, Cabo Ortegal Complex, NW Iberian Massif)

Procedencia del margen continental subducido a HP-HT a c. 390 Ma (Citurón Varisco, Complejo de Cabo Ortegal, NO del Macizo Ibérico)

R. Albert[1], R. Arenas[2], A. Gerdes[1, 3], S. Sánchez Martínez[2] and L. Marko[1]

1 Institut für Geowissenschaften, Goethe University Frankfurt, 60438, Frankfurt. r.albert@geo.ucm.es
2 Dpto. de Petrología y Geoquímica e Instituto de Geociencias (UCM, CSIC), Universidad Complutense, 28040, Madrid
3 Dpt. of Earth Sciences, Stellenbosch University, Private Bag X1, Matieland

Abstract: The Variscan Upper Allochthon is a continental-affinity terrane that recorded a Cambrian–Ediacaran magmatic arc generation, a subsequent transition to a passive margin, and a collision-related high-P metamorphism during the Devonian–Carboniferous amalgamation of Pangea. The bottom member of the Upper Allochthon recorded this HP-HT Devonian metamorphism, which was attained by a subduction process. To know which continental margin subducted a provenance study was carried out on the metasedimentary rocks of the Banded Gneisses (5 samples), which form part of the Upper Allochthon subducted terrane. The provenance of this terrane has been established using combined U–Pb (n = 613) and Lu–Hf (n = 463) isotopic LA–ICP–MS zircon analyses. These data show that the Variscan Upper Allochthon has a West African provenance and therefore, it strongly suggests that the NW Iberian allochthonous complexes and their correlative European terranes are also West Africa derived. These results allow us to finally clarify that the first high-P event, recorded during the eo-Variscan amalgamation of Pangea, was attained by the subduction of the margin of Gondwana under the colliding retro-continent, presumably Laurussia.

Key words: Cabo Ortegal; Banded Gneisses; Lu–Hf; U–Pb; Upper Allochthon.

***Resumen:** El Alóctono Superior Varisco es un terreno de afinidad continental que registró una generación de arcos magmáticos en el Cámbrico-Ediacarense, una subsecuente transición a margen pasivo y un metamorfismo de alta presión relacionado con una colisión continental, relacionada a su vez con la amalgamación de Pangea en el Devónico-Carbonífero. El miembro inferior de este Alóctono registró este metamorfismo Devónico de alta-P y alta-T, el cual se desarrolló en un evento de subducción. Para saber qué margen continental subdujo, se ha llevado a cabo un estudio de procedencia en la rocas metasedimentarias (5 muestras) de una de las formaciones de este Alóctono, los Gneises Bandeados (Gneises Eclogíticos). La procedencia de este terreno ha sido establecida combinando análisis isotópicos LA-ICP-MS de U-Pb y Lu-Hf en circón. Estos datos muestran que el Alóctono Superior Varisco procede del Cratón Africano Occidental, y que por lo tanto los complejos alóctonos del NO del Macizo Ibérico y sus terrenos correlacionables en Europa también han de tener una procedencia Gondwánica. Estos resultados nos permiten afirmar claramente que el primer evento de alta-P registrado en la amalgamación eo-Varisca de Pangea, se debió a la subducción del margen de Gondwana bajo el retro-continente, presumiblemente Laurrusia.*

***Palabras clave:** Cabo Ortegal; Gneises Bandeados; Lu–Hf; U–Pb; Alóctono Superior.*

INTRODUCTION

The Variscan belt is a long orogen developed during the main stages of the Pangea assembly as a result of the collision of two large continents, Gondwana to the South and Laurussia to the North. This orogen can be followed from Iberia, across Brittany and the French Massif Central, to the Bohemian Massif, and has continuity in eastern North America, in the Appalachian–Alleghanian belt. The orogen is characterized by the development of two high-P events with different ages, preserved in two distinct terranes with continental or transitional characteristics (upper and basal units), which are separated by an ophiolite terrane considered as the suture zone of the orogen.

The high-P event registered by the basal units is known to have taken place at c. 370 Ma by the subduction of Gondwana under, presumably, Laurrusia. The other high-P event, registered by the upper units (Upper Allochthon), is known to have occurred at c. 390 Ma. The provenance of this upper terrane was assigned to Gondwana by studying its top intermediate-P member (Albert et al., 2015), but no studies have been carried out on its HP-HT bottom member. It has been traditionally assumed that the Upper Allochthon is a single terrane, but no clear proves have been presented. This communication presents a provenance study of the HP-HT bottom member of the Upper Allochthon to prove the single or composite nature of this terrane and to assess the provenance of the continental margin that subducted in the first high-P event recorded in the eo-Variscan assembly of Pangea.

GEOLOGICAL FRAMEWORK

The Galicia-Trás-os-Montes Zone (GTOMZ) is the most external Zone, in relation to the Gondwana mainland, compared to those that form the Iberian Massif. This Zone contains the NW Iberian allochthonous complexes, which lie as huge synformal structures on top of the Parautochthon domain (also part of the GTOMZ). These complexes are broadly divided into three terranes (from bottom to top: basal, ophiolitic and upper units). This article focusses on the HP-HT bottom member of the upper units (Upper Allochthon) of one of these complexes: the Cabo Ortegal Complex.

SAMPLE DESCRIPTION

Five metasedimentary rock samples were chosen from the Banded Gneiss formation. This formation is one of many that altogether form the HP-HT bottom member of the Upper Allochthon of the Cabo Ortegal Complex. All samples are variably fresh (not altered) fine grained migmatitic para-gneisses with granolepidoblastic texture.

RESULTS

U–Pb results

Analyses from all samples add a total of 729 age determinations, of which 613 were concordant (<10% discordance, d = 15.9%). Of the analyses, 34.7% (n = 213) have a Palaeozoic–Neoproterozoic age with peaks at c. 512, 522, 545, 561, 575, maximum abundance at 522–512 Ma, and a tail with minor peaks between 780 and 590 Ma. Mesoproterozoic ages are scattered in the interval age of c. 1.6–1.1 Ga and do not define any maximum, comprising 2.8% (n = 17) of the total ages. The main age group is Paleoproterozoic (39.6%, n = 243) and the majority of the ages are constrained between c. 2.14 and 1.88 Ga with a well-defined maximum at 2.07 Ga. The Archean population represents 22.8% (n = 140) of the analyses and shows two main groups, one with ages concentrated at 2.52–2.48 Ga (maximum at c. 2.51 Ga), and a second group ranging 2.68–2.61 Ga (maximum at 2.64 Ga). Maximum depositional ages (MDA) calculated for each of the five samples vary from 521 to 497 Ma. As this MDA age-spread is relatively high the older MDA was chosen (c. 521 Ma) to establish the MDA for this formation.

Lu–Hf results

From the 613 concordant zircon cores analysed with the U–Pb method, 463 were analysed for Lu–Hf isotopes. Palaeozoic–Neoproterozoic zircon is arranged in the Hf–U–Pb age diagram in two ways (Fig. 1). Firstly, as a vertical array of zircon with crystallization ages between c. 590 and 490 Ma, and secondly, with ages of c. 780–590 Ma. A group of zircon values (n = 19), which are mainly Mesoproterozoic (1615–978 Ma), plot around the CHUR evolution trend. Paleoproterozoic 2.14–1.88 Ga zircon population is arranged as a group with an horizontal array, composed by 78% (n = 104) of this Paleoproterozoic zircon, and as a vertically arranged group (n = 29, 22%). Paleoproterozoic and Archean zircon (n = 128) has crystallization ages between c. 3.01 and 2.19 Ga, and they are horizontally arranged (Fig. 1).

DISCUSSION

The distal (>1 Ga) detrital zircon spectrum

The main Archean U–Pb zircon population (22.8%) in the Banded Gneisses is bracketed at 2.75–2.50 Ga (Fig. 1). Its horizontal linear evolution from intrusion at c. 2.70 to 2.40 Ga could represent a long-lasting continental crust reworking process, or Pb-loss processes triggered by high grade metamorphic events (Fig. 1). In the Northern WAC, Archean igneous rocks have mainly been reported in the Western Reguibat Rise (see references in Albert et al. 2015), and therefore this Rise is most probably the source area for the Banded Gneisses Archean zircon. The Paleoproterozoic fraction falls within the time span of the Eburnean orogeny, and therefore the

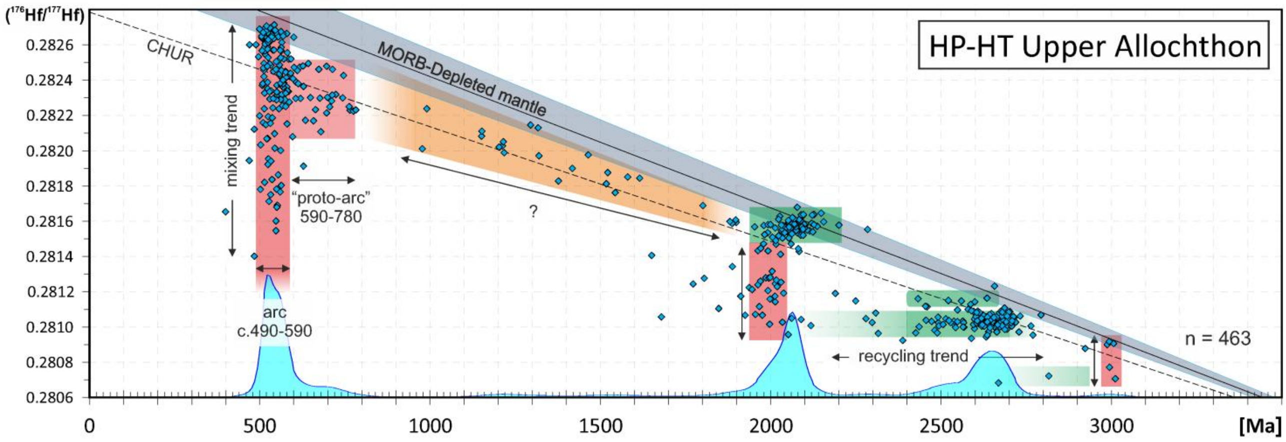

FIGURE 1. ^{176}Hf/^{177}Hf v. age plot for detrital zircon data. Horizontal green shaded areas represent recycling trends with ^{176}Lu/^{177}Hf = 0. Vertical red shaded areas represent mixing between juvenile and recycled crustal material formed in magmatic arcs. The orange shaded area represents a source that developed through time with a similar ^{176}Lu/^{177}Hf ratio as the CHUR and depleted mantle, from which the Mesoproterozoic zircon crystallized.

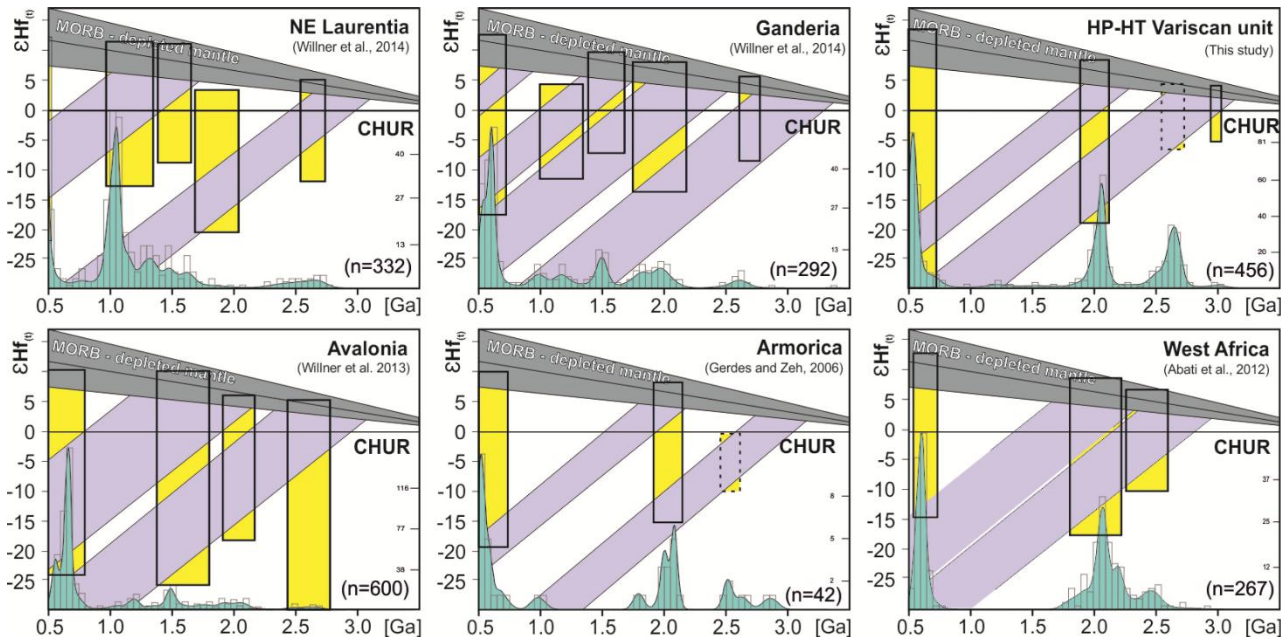

FIGURE 2. Schematic εHf(t) v. age for detrital zircon from data presented herein and from Gerdes & Zeh (2006), Abati et al., (2012) and Willner et al., (2014). Light purple shaded areas represent crustal evolution trends of zircon that might have originated from common crustal domains. Vertical yellow shaded areas represent mixing between juvenile and recycled crustal material, most likely formed in magmatic arcs. Light blue shaded areas at the base of each plot are adaptive kernel density distributions of the considered zircon. Figure modified from Willner et al., (2014).

Paleoproterozoic materials of the Banded Gneisses are probably derived from rocks generated or reworked during this orogeny. The Banded Gneisses Hf/Hf data (Fig. 1) for zircon of Eburnean age (c. 2.20–1.88 Ga, n = 135) are arranged as a cluster (n = 96/135) representing isotopically depleted rocks and as a vertical arrangement (n = 39/135), suggesting a mixing process, i.e. Eburnean DM derived magmas intruding an older crust triggering mixing processes (Fig. 1). As the values with lower Hf/Hf ratios in this group have the same ratios than the Archean data, this old crust could well be the one represented by the Banded Gneisses Archean zircon. In the Mesoproterozoic Era, the WAC became a stable craton which resulted in a characteristic c. 1.7–1.0 Ga 'magmatic gap'. In the Banded Gneisses the Mesoproterozoic zircon is scarce and scattered, constituting 2.8% of the total population and not defining a clear maximum (Fig. 1). Taking into account the isotopically depleted signature of this population (Fig. 1), it could have been derived from the Amazonia craton or from Mesoproterozoic dykes intruding the WAC. Terranes that clearly derive from the Amazonian craton and have similar Neoproterozoic–Cambrian arc developments as the Upper Allochthon (Avalonia and Ganderia), contain depleted Mesoproterozoic zircon, but not as depleted as zircon from this study (Fig. 2). Dolerite dykes have been recently discovered in the Anti-Atlas belt with emplacement ages of c. 1.65 Ga and c. 1.4 Ga. Fig. 1 shows that the HP–HT Upper Allochthon Mesoproterozoic population seems to have a source that undertook a similar Lu/Hf isotopic evolution as the CHUR-depleted mantle. These observations seem to favour a WAC juvenile dyke provenance rather than an Amazonian or even a Laurentian source.

The proximal (<1 Ga) detrital zircon spectrum

The Palaeozoic–Neoproterozoic zircon ages of the Banded Gneisses coincide with the reported ages for the Cadomian orogeny (c. 750–540 Ma; Linnemann et al., 2014), but the c. 522–512 Ma Banded Gneisses maximum is younger, suggesting a late development of the Cadomian orogeny. Banded Gneisses zircon with ages between c. 780 and 590 Ma are not abundant and plot around the CHUR evolution trend (Fig. 1), pointing to a crustal recycling due to the initial development of the Cadomian arc system ('proto–arc' stage; Fig. 1). The c. 590–490 Ma Banded Gneiss zircon is very abundant and shows a vertical arrangement in its Hf/Hf isotopic pattern (Fig. 1). This pattern can be explained by the intrusion of juvenile magmas that triggered mixing processes with an Eburnean and Archean crust (and with a small proportion of reworked early Cadomian crustal material), consistent with a peripheral arc activity at the Northern WAC.

According to the data presented, the MDA for the siliciclastic series of the HP–HT upper units is c. 521 Ma. Taking into account crystallization ages of intrusive igneous rocks in this formation (c. 512–470 Ma, Albert, 2016), the protolith of the eclogite facies paragneisses of the Cabo Ortegal Complex was a Middle Cambrian siliciclastic sedimentary series. The protoliths of the sedimentary rocks involved in the Banded Gneiss formation may have well been deposited in a back-arc type basin, where the volcanic arc system was very active, shedding its juvenile materials into the basin at the same time as the adjacent WAC supplied the Eburnean and Archean detritus.

Provenance of the HP–HT Upper Allochthon

The HP–HT Upper Allochthon zircon detrital signature has been compared (Fig. 2) to cratons and terranes that could potentially be the source areas for the studied meta-sedimentary rocks. This figure shows a provenance incompatibility between the studied terrane and the Avalonian terranes of Avalonia and Ganderia, and the Laurentian craton. Provenance compatibility is shown with the West Africa craton and with the Armorican terrane, which is also WAC derived.

CONCLUSIONS

The IP and the HP–HT upper units

The main difference between their U–Pb age density distributions is that the Banded Gneiss formation (HP-HT) has an abundant c. 590–540 Ma Ediacaran population (Fig. 1) and the Cariño Gneiss formation has not (IP, Albert et al., 2015). Both have very similar detrital sources. Their bimodal detrital populations suggest that both formations had the same geological setting, i.e. sedimentation in a back-arc type basin. Their MDAs and Lu-Hf values are very similar. For all these reasons both formations represent the same section of the Gondwanan margin, and therefore both constitute part of the same terrane. The first sediments deposited were those of the Banded Gneiss formation (due to its higher isotopic heterogeneity and higher presence of intruded igneous rocks), formed by the mixture of the old components from the WAC (Eburnean and Archean detritus) and abundant arc related c. 590–520 Ma sediments. The Cariño Gneiss protoliths deposited afterwards, filling the same basin with WAC sediments (Albert et al., 2015) and c. 560–510 Ma arc-derived sediments (Andonaegui et al., 2016).

Implications for the c. 390 Ma subduction

The metasedimentary sequences that constitute the gneissic units of the Upper Allochthon have the same detrital sources (WAC) and they seem to have been deposited in a same back-arc basin. Therefore, these units were probably members of the same sedimentary succession. Between the time of deposition (c. 512–506 Ma) and high-grade metamorphism (c. 400–390 Ma), both formations constituted a part of the margin of Gondwana. According to the sedimentary and igneous processes recorded in this margin, it changed from a volcanic arc to a passive margin (Cambrian–Ordovician boundary), and after a short event of extension it subducted at c. 400–390 Ma. This deep subduction affecting the margin of Gondwana is considered a clear evidence for a first collision between this continent and the southern margin of Laurussia (Arenas et al., 2014). The new provenance data presented herein is conclusive on the origin of the Banded Gneiss formation, whose eclogite facies can only be explained as generated during subduction at c. 390 Ma of the Gondwana margin below the retro-continent located to the North, most probably Laurussia. This event represents a first collision related to the final assembly of Pangea, as has been recently proposed (Arenas et al., 2014). Considering the original linear character of the Variscan belt and the presence of a rather continuous equivalent HP–HT unit from the Iberian Massif to the Bohemian Massif, we suggest that the conclusions presented herein can be extrapolated to the entire Variscan realm.

ACKNOWLEDMENTS

Financial support has been provided by the Spanish project CGL2012-34618 (Ministerio de Economía y Competitividad).

REFERENCES

Abati, J., et al. (2012): Insights on the crustal evolution of the West African Craton from Hf isotopes in detrital zircons from the Anti-Atlas belt. *Precambrian Research*, 212: 263–274.

Albert, R., et al. (2015): Provenance of the Variscan Upper Allochthon (Cabo Ortegal Complex, NW Iberian Massif). *Gondwana Research*, 28: 1434–1448.

Albert, R., (2016): The Eclogitic Gneisses of the Cabo Ortegal Complex: Provenance and tectonothermal evolution (zircon U-Pb/Lu-Hf methods). Doctoral thesis, Complutense University of Madrid, 355 p.

Arenas, R., et al. (2014): Two-stage collision: Exploring the birth of Pangea in the Variscan terranes. *Gondwana Research*, 25: 756–763.

Andonaegui, P., et al. (2016): The last stages of the Avalonian-Cadomian arc in NW Iberian Massif: isotopic and igneous record for a lomg-lived peri-Gondwanan magmatic arc. *Tectonophysics*, Submitted.

Gerdes, A. y Zeh, A. (2006): Combined U-Pb and Hf isotope LA–(MC–)ICP–MS analyses of detrital zircons: comparison with SHRIMP and new constraints for the provenance and age of an Armorican metasediment in Central Germany.*Earth and Planetary Science Letters*, 249: 47–61.

Linnemann, U., et al. (2014): The Cadomian Orogen: Neoproterozoic to Early Cambrian crustal growth and orogenic zoning along the periphery of the West African Craton—Constraints from U-Pb zircon ages and Hf isotopes (Schwarzburg Antiform, Germany). *Precambrian Research*, 244: 236–278.

Willner, A.P., et al. (2014). Crustal evolution of the Northeast Laurentian Margin and the Peri-Gondwanan microcontinent Ganderia prior to and during closure of the Iapetus Ocean: detrital Zircon U-Pb and Hf isotope evidence from Newfoundland. *Geoscience Canada*, 41: 345–364.